Numerical Simulation of Fire Spreading in a Steel Skeleton-Drywall System Building

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Abstract

Fire protection systems in buildings are commonly regulated using prescriptive-based codes and standards, which exhibit small flexibility for innovative solutions and cost-effective designs. Performance-based fire safety design can alleviate such restrictions and several countries have started to adopt such methodologies in the recent years. In this context, the utilization of Computational Fluid Dynamics (CFD) tools to accurately describe the fire and its impact on buildings and people is gaining significant momentum in the fire safety engineering community. In this work, a CFD tool is used to study the thermal behaviour of a two-storey residential house subjected to a typical domestic fire scenario. The building comprises a steel-skeleton with drywall systems as partitions and external cladding; the walls consist of multiple layers of plasterboard and insulation materials. When plasterboard is subjected to a high temperature environment, water molecules bound in its crystal lattice are released; this “dehydration” process is expected to enhance the building’s fire resistance.

The Fire Dynamic Simulator code is used to simulate the momentum-, heat- and mass-transfer phenomena occurring inside the building during the fire. The Large Eddy Simulation concept together with a mixture-fraction model are used to describe the developing reactive turbulent flow and the combustion phenomena, respectively. The physical properties of the utilized multi-layered building components are taken into account in the simulations to accurately describe their thermal response; the highly detailed computational geometry is based on actual architectural drawings.

Numerical predictions of the temporal evolution of a range of fire safety related quantities, such as gas velocity, gas- and wall-temperatures and toxic gas concentrations are obtained for the entire 3-dimensional domain that represents the interior of the building. Gas velocity and temperature predictions are used to visualize the developing flow-field and to estimate the heat flux to which each building element is exposed. Predicted wall temperatures allow the assessment of the investigated type of building in terms of fire resistance. Finally, gas temperature and toxic gas concentration predictions enable risk assessment for the tenants of the building in the event of a fire.

Keywords: fire safety, CFD, drywall systems, gypsum plasterboard

1. Introduction

1.1 Residential Fires

Fire is arguably one of the most complex phenomena considered in combustion science, since it embraces nearly all the effects found in subsonic chemically reacting flows. Fluid dynamics, combustion, chemical kinetics, radiation and multi-phase flow effects are linked together to provide an extremely complex physical and chemical phenomenon. It is this complexity which delayed the development of fire research as a science until the 1950s. Fires are associated with a large range of hazards to humans, property and the environment. Amongst the variety of incidents of uncontrollable fires, unwanted fires in enclosures are the most frequently encountered (Yeoh and Yuen, 2009). In building fires, the confined space controls the air supply and thermal environment of the fire, which affect the spread and growth of the fire, its maximum burning rate and its duration. Fire safety regulations have a major impact on the overall design of buildings with regard to layout, aesthetics, function and cost.

According to National Fire Protection Association there were 1,451,500 fires in the United States in the year 2008 (Karter, 2009). 84% of all fire fatalities occurred in homes, i.e. one- and two-family dwellings and apartments. The most important areas of origin in residential fires are the kitchen (34%), the bedroom (12%) and the living room (6%) (Madrzykowski and Hamins, 2007). Fires that started by lighted tobacco products occur mainly in either the bedroom or the living room and constitute the leading cause of residential fire deaths (Ahrens et al., 2004). Cooking fires are often the result of the ignition of loose clothing or other nearby flammable materials from unattended cooking where grease or oil ignites. In 2003, there were 118,700 reported cooking-related home structure fires in the U.S.A., which resulted in 250 fatalities, 3880 injuries and $512 million in direct property damage (Hall, 2006).

1.2 CFD Simulation of Fires in Buildings

Design for fire safety engineering is increasingly moving towards the use of performance-based fire-safety regulations due to the restrictive nature of the "conventional" prescriptive regulations. Performance evaluation allows the trade-off between many alternative design options to provide the required level of safety. The need for design tools to aid in demonstrating compliance with performance-based regulations has resulted in the widespread use of fire modelling techniques by designers and practitioners in many areas of fire protection design. Fire safety science has grown significantly over the last twenty years. However, the mathematical modelling of fire is still a rapidly developing area, due to the extreme complexity of the emerging physical and chemical phenomena. The underlying fluid dynamics, turbulence and combustion phenomena have not yet been fully resolved, still representing significant challenges for the scientific community.

In recent years, a variety of numerical tools has been developed to enable the prediction of fire growth within enclosures. Computational Fluid Dynamics (CFD) tools allow the numerical solution of the fundamental equations describing the transfer of mass, momentum and energy in an enclosure fire environment. These tools have been successfully used in a variety of fire safety areas, such as fire protection engineering (e.g. prediction and visualization of fire and smoke movement), building architectural design (prediction of fire behaviour to estimate the optimal place for fire exits or sprinkler placement and operation), fire safety strategy for a building (e.g. prediction of smoke flow patterns to estimate the optimal design of smoke control systems), accident investigation, building re-design etc. The role of CFD tools in fire research is steadily increasing as the models become progressively robust and sophisticated and validation studies make them more reliable. The CFD approach is considered to be fundamental to the future development of fire models which can provide the basis for performance-based fire safety regulations.

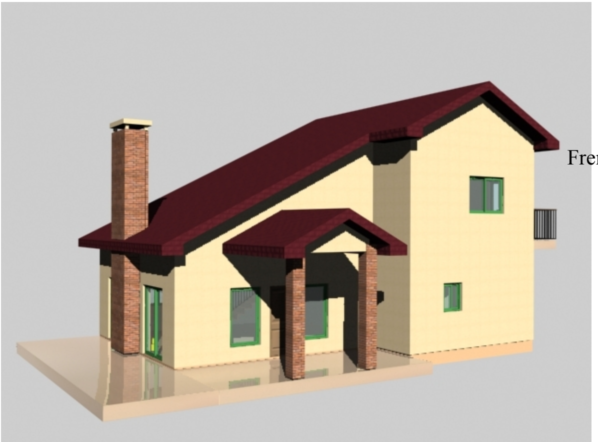
In this context, the use of CFD tools is necessary to extend beyond simplified geometrical configurations in order to ascertain their applicability in real building fires (Yeoh and Yuen, 2009). However, most of the available studies focus mainly in single-room or two-room simulations, e.g. (Hasib et al., 2007, Merci and Maele, 2008). Scarce reports are available in the open literature regarding multi-room compartment fire simulations; they mainly focus on the investigation of accidental fires in restaurants (Vettori et al., 2002) or single-family dwellings (Rein et al., 2006). A round-robin study performed recently has revealed the difficulties associated with modelling fire dynamics in complex fire scenarios using CFD tools, suggesting that the respective accuracy of fire growth predictions is still generally poor (Rein et al., 2009). The main scope of the present study is to investigate the ability of currently available CFD tools to effectively simulate the flow- and thermal-fields developing in a full-scale two-storey residential house during a fire accounting for detailed material properties.

1.3 Fire Resistance of Drywall Systems

Gypsum plasterboards are widely used in the building industry for a variety of applications as an aesthetically pleasing, easily applied and mechanically enduring facing material for walls and ceilings. In the context of building fire safety, gypsum plasterboards are capable of decelerating the penetration of fire through walls and floors, due to the endothermic gypsum dehydration process occurring in high temperatures. When a plasterboard is subjected to a high temperature environment, water molecules bound in its crystal lattice are released and transferred through the board, absorbing energy and thus reducing the mean wall temperature. This “dehydration” process is known to improve the global fire resistance of the building and it is suggested to enhance the safety margins of the building, by allowing longer evacuation times (Wang and Ang, 2004).

2. Drywall System Building

The modelled two-storey, 125m^2, residential house represents a typical Greek family two-storey dwelling, with a typical residential arrangement plan (ground floor: kitchen, office and living room, first floor: master and auxiliary bedroom). The house is constructed using a load-bearing steel frame, combined with gypsum plasterboard wall assemblies. Gypsum plasterboards are installed in double cladding layers in accordance with the fire-resistance, thermal and sound insulation requirements.



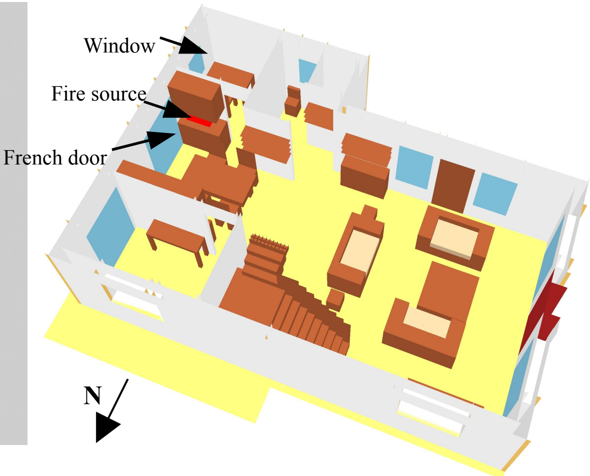


Figure 1: Photorealistic view of the building (left) and numerical grid of the ground floor (right).

The external walls of the house are multi-layered, consisting construction of (from the interior to the exterior) two 12.5mm plasterboards joined together, a 182.5mm void (allowing space for the steel frame and plumbing), a 12.5mm plasterboard, a layer of 80mm rockwool, a 12.5mm cementboard and a final layer of 50mm EPS polystyrene (Figure 2). The internal walls consist of two 12.5mm plasterboards, a layer of 80mm rockwool and two 12.5mm plasterboards.

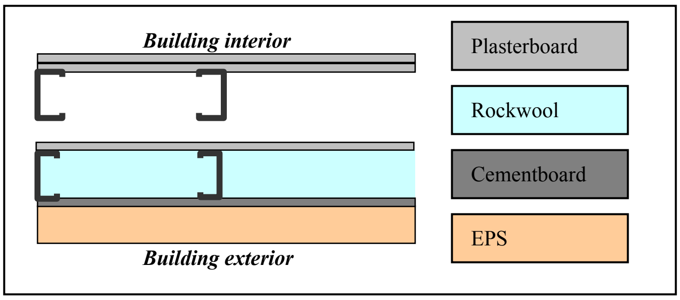


Figure 2: Cross-section of the external wall.

3. Numerical Simulation

3.1 Description of the CFD code

The Fire Dynamics Simulator (FDS) code is a CFD tool aimed at solving practical fire problems in fire protection engineering, while at the same time providing a tool to study fundamental fire dynamics and combustion. The FDS code solves numerically a form of the Navier-Stokes equations appropriate for low-speed, thermally driven flow with an emphasis on smoke production and heat transfer from fires. The core algorithm is an explicit predictor-corrector scheme that is second order accurate in space and time. Turbulence is treated by using the Large Eddy Simulation (LES) approach. The subgrid-scale turbulence is simulated using the Smagorinsky model, utilizing a Smagorinsky constant value of 0.2. The numerical time-step is continuously adjusted in order to satisfy the CFL criterion. The partial derivatives of the conservation equations of mass, momentum and energy are approximated as finite differences and the solution is updated in time on a three-dimensional, Cartesian grid. Thermal radiation is simulated using the finite volume methodology on the same grid as the flow solver. All solid surfaces are assigned thermal boundary conditions by taking into account information about the burning behaviour of the respective material.

3.2 Details of the Simulation

Computational Grid

The two levels of the house are enclosed within a rectangular volume, measuring 12.8m, 11.2m and 8m, in the x-, y- and z- directions respectively. The physical volume is divided into 798,720 cubic computational cells, each having a side of 0.1m. Certain construction and decorative details are "roughly" approximated in order to limit the size of the computational grid required for the simulations. However, the house is completely furnished following a standard residential configuration.

Initial and Boundary Conditions

At the beginning of the numerical simulation (t=0s), the entire computational domain (both indoors and outdoors) is assumed to be still (zero velocity), exhibiting a temperature of 20ºC. The total simulation time was 15min, in order to be able to capture with sufficient detail the most important characteristic stages of the developing fire, namely initiation, spreading and decay. The total CPU-time needed for the complete simulation was approximately 24 hours on a 4GB Quad Core 2.4GHz desktop PC, using the "parallel computation" version of the FDS code.

Cooking equipment is the primary cause of reported home fires and home fire injuries in the U.S.A. (Ahrens et al., 2004). In this study, the ignition source was assumed to be a typical cooking fire represented by a 0.8m by 0.2m rectangular "patch" located on the upper surface of the birch wood kitchen bench. A constant 300kW fire was assumed to appear at t=0s; the fire power was selected according to relative suggestions in the literature regarding fires related to kitchen equipment and cooking vegetable oil (Luo and Beck, 2004).

Physical Properties of the Building Materials

The thermo-physical properties (Table 1) of the construction and furniture materials used in the house were obtained from the open literature (Prasad, 2009, Hostikka, 2008).

Table 1: Thermo-physical properties of the materials used in the simulations.

Material	***Thermal Conductivity k* (W/mK)**	***Specific Heat Cp* (kJ/kgK)**	***Density ρ* (kg/m³)**
Upholstery	*0.05*	*1.0*	*23*
Birch wood	*0.22*	*2.2*	*550*
Char	*0.2*	*3.5*	*94*
Polystyrene	*0.039*	*1.21*	*15*
Cementboard	*0.35*	*0.879*	*1280*
Rockwool	*0.035*	*1.0*	*50*

The physical properties of gypsum are varying with increasing temperatures, due to the occurring chemical reactions (dehydration). The utilization of temperature-dependent physical properties is known to yield more accurate results in heat transfer simulations of gypsum plasterboards, compared to mean values (Kontogeorgos et al., 2008). Therefore, temperature-dependent values for thermal conductivity and specific heat are used in the current simulations (Figure 3). The thermal conductivity variation in a commercial plasterboard has been measured using the hot wire method, whereas the specific heat temperature profile is obtained from the literature (Wakili et al., 2007).

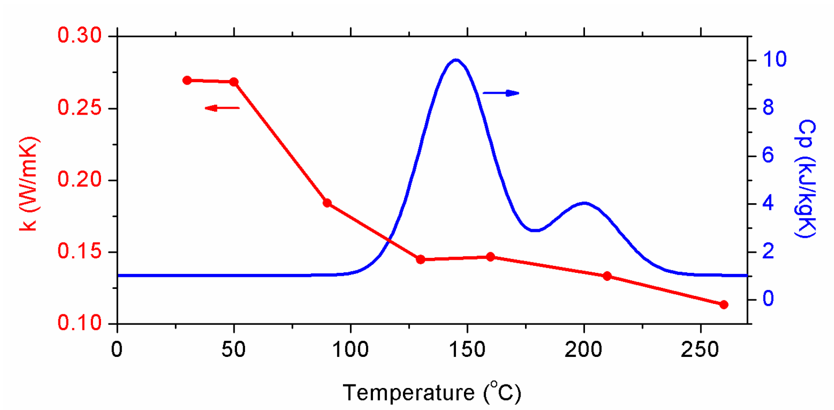


Figure 3: Temperature dependent physical properties of gypsum plasterboard.

Numerical Modelling of Combustion and Pyrolysis

The selection of the proper physical properties and pyrolysis rate coefficients for the combustible materials is a very challenging task; especially for the latter, values derived from small and large-scale experiments may exhibit differences of several orders of magnitude (Hostikka and McGrattan, 2001). The simulated house was assumed to be equipped mainly with wooden furniture. A single step Arrhenius reaction is used to model the thermal decomposition of wood. The kinetic and thermal parameters used in the simulations were found in the literature (Matala, 2008); the respective values are presented in Table 2. Also, it was assumed that 17.2% of the combustible wood is converted to char (Matala, 2008); the respective thermo-physical properties are given in Table 1.

The combustible gases produced by wood pyrolysis were considered to be described by the collective chemical species $C_{3.4}H_{6.2}O_{2.5}$ (Ritchie et al., 1997). A two-step mixture fraction model was used to simulate combustion. The (fixed) yield of carbon monoxide (CO) was assumed to be 0.004 kg CO/kg wood (DiNenno et al., 2002).

Table 2: Kinetic parameters used to simulate wood pyrolysis.

Parameter	***Value***	***Parameter***	***Value***
Pre-exponential factor A (s^{-1})	7.51×10^{11}	*Reaction order* N_S	*3.12*
Activation energy E (kJ/kmol)	1.61×10^{5}	*Heat of combustion* ΔHc *(kJ/kg)*	*14500*

3.3 Parametric Study

The computational domain extends approximately 2.0m outwards from each side of the house; therefore, airflow in the surrounding environment can be also simulated, thus allowing studying of the effects of open external doors or windows. Three different scenarios have been developed in order to investigate the effect of ventilation in the fire spreading rate. In the first (Test Case 1), which served as a basis for comparison, all external house openings (doors and windows) were considered closed whereas all the internal openings were considered to be fully open. As a result, no gas flow was allowed to occur from the inside of the house to the surrounding environment and vice versa. However, the indoor and outdoor fields still interact with each other, by means of heat conduction through the external walls of the house. In the 2nd Test Case, the eastern French door (1.6m x 2.2m), located very close to the fire source, is considered to be fully open, thus providing large amounts of fresh air into the main combusting zone (c.f. Figure 1). Finally, Test Case 3 corresponds to an open window (0.8m x 1.0m), which is located in a room adjacent to the kitchen. The performed parametric study aims to investigate the impact of alternative ventilation schemes which are known to have a significant effect on the characteristics of fire development (under-ventilated, well-ventilated fires).

4. Results and Discussion

4.1 Predictions of the Developing Flow-field

A characteristic image of the developing flow-field is presented in Figure 4, which depicts predictions of the instantaneous gas phase velocity vectors over a vertical plane, 9min after the initiation of the fire for the three investigated scenarios. In all cases, the largest velocity values are observed near the fire region, where the thermally induced buoyancy phenomena are very strong due to the large temperature gradients. A typical stratified fire-induced flow field is developed in the house; the large density variation forces the mixture of air and combustion products to rise, leading to the consequent entrainment of the cold ambient air to the lower part of the house. The strong buoyant upward flow from the kitchen room door to the ceiling of the living room is clearly visible. Compared to Test Case 1 (Figure 4, left), the entrainment of fresh air from the surrounding environment, either through the

French door in Test Case 2 (Figure 4, middle) or through the nearby window in Test Case 3 (Figure 4, right), renders the developing flow-field more intense, exhibiting higher velocities.

Figure 4: Predictions of velocity vectors 9min after the fire initiation.

4.2 Predictions of the Developing Thermal-field

Predictions of the gas temperature temporal evolution over a vertical plane are depicted in Figure 5. As expected, the highest temperatures are observed in the region just above the fire source, where the main fire plume is established. Due to the large indoor openings that do not impede flow circulation and the large volume of the entire house, which serves as a "thermal fly-wheel" not allowing the local temperatures to rise significantly, "conventional" flashover is not observed. The stratification of the developing flow-field leads to the formation of a similarly stratified thermal field. Fresh air entrainment through the French door (Test Case 2) and the window (Test Case 3) is evident in the lower part of the kitchen room (Figure 5, middle) and the nearby room (Figure 5, right), respectively. A similar thermal stratification, although less distinct, also develops in the upper floor, where relatively high temperatures are observed in the well-ventilated fire scenarios (Test Cases 2 and 3).

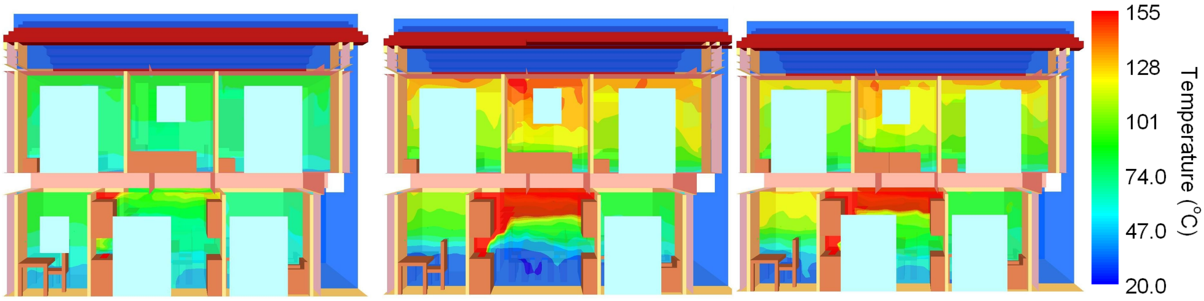


Figure 5: Predictions of gas mixture temperature 9min after the fire initiation.

CFD simulations allow the estimation of fire resistance of entire buildings. In this context, the mechanical strength of gypsum plasterboard wall assemblies is investigated. It should be noted here that plasterboard walls are not load-bearing, therefore their failure cannot contribute in case of partial collapse of the building. Gypsum plasterboards exposed to fire are considered to exhibit mechanical failure when cracks or openings are observed through the wall (Manzello et al., 2007); however, since cracking phenomena cannot be accurately simulated in the CFD code, alternative failure criteria had to be used. According to the Australian Standard AS1530.4, a plasterboard wall fails when the maximum temperature rise (above the ambient temperature) of the ambient facing side exceeds 180°C (Clancy, 2002).

Surface temperature predictions for the external kitchen wall, which lies closer to the fire source, are depicted in Figure 6. It is evident that the exterior side of the wall assembly (which consists of multiple layers of plasterboard, cementboard and insulating materials, c.f. Figure 2) exhibits a very modest temperature rise. However, the interior side (comprising two gypsum plasterboards joined together, c.f. Figure 2), which is located very close to the fire source, reaches high temperature levels; in fact, its "unexposed" side, exceeds the "limiting" temperature of 200°C, approximately 6min after fire initiation. The gradual decrease in the wall temperature observed in Test Case 1, suggests that the lack of fresh air entrainment results in the fire becoming under-ventilated.

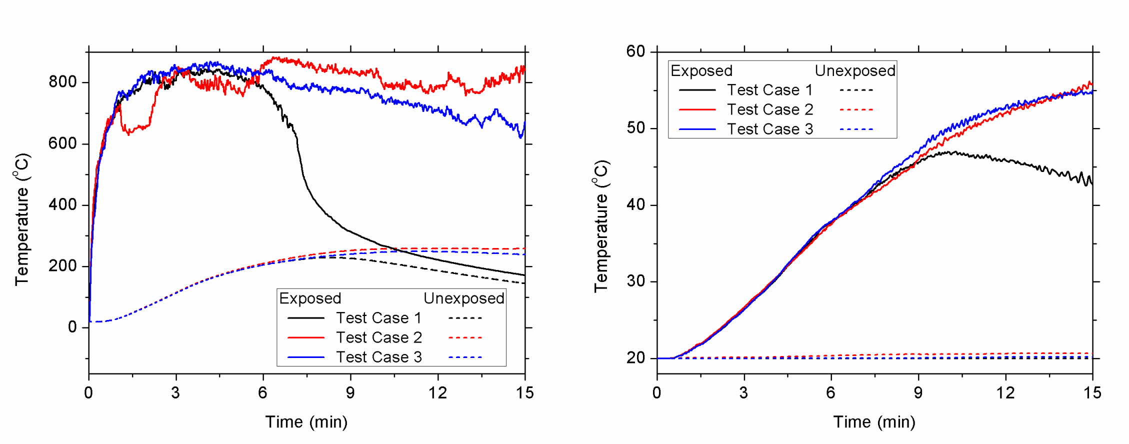


Figure 6: Temporal evolution of the surface temperature of the interior (left) and the exterior (right) assembly of the external kitchen wall.

4.3 Occupant Tenability

In order to evaluate life safety in fire conditions using a numerical modelling tool, quantitative tenability criteria are needed. An average person exposed for more than a few minutes to high levels of temperature and heat flux, is likely to suffer burns and die, either during or immediately after exposure, mainly due to hyperthermia. Respective values for the reported tolerance times in various temperatures are given in Table 3 (DiNenno et al., 2002); tenability limits for incapacitation or death due to exposure to common asphyxiant products of combustion, are also presented.

Table 3: Reported tolerance time for exposure to warm air and tenability limits for exposure to common asphyxiant products of combustion

Dry air temperature (°C)	***Reported tolerance time (min)***	***Asphyxiant products***	***5min (Incapacitation)***	***30min (Death)***
126	*7*	***CO***	*6000 - 8000 ppm*	*12000-16000 ppm*
180	*4*	***O_2***	*10-13 %*	*< 5%*
205	*3*	***CO_2***	*7-8 %*	*> 10%*

Temperature predictions in the kitchen room (Figure 7, left) suggest that this region quickly becomes untenable in all the considered test cases. The limiting effects of oxygen deprivation on the fire evolution in Test Case 1 are again evident (under-ventilated fire conditions). However, in the upper floor, the reported tolerance time is exceeded only in Test Case 2, when well-ventilated fire conditions are established (Figure 7, right).

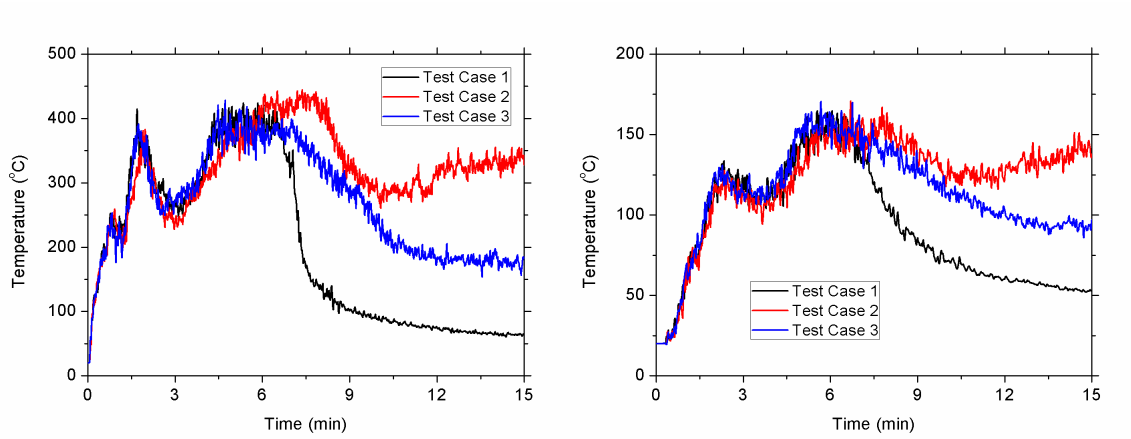


Figure 7: Time evolution of gas temperature in the middle of the kitchen, at a height of 2.4m (left) and in the 1st floor gallery, at a (global) height of 5.4m (right).

Predictions of combustion products concentrations in the kitchen room are depicted in Figure 8; in this case, the reported tenability limits (Table 3) are not exceeded in any of the considered test cases. It is well known that significant toxicity issues arise due to the incomplete combustion in the case of ventilation-limited fires (Quintiere, 2006). As it can be clearly seen in the CO concentration predictions of Test Case 1 (Figure 8, right), when the fire becomes under-ventilated (approximately 8min after fire initiation, see also Figure 7), the respective concentration levels exhibit a sudden increase.

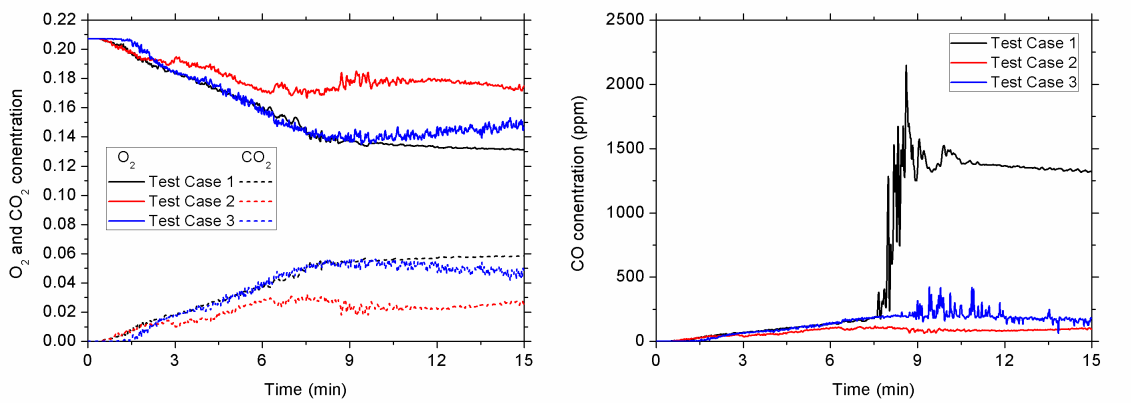


Figure 8: Time evolution of O_2 and CO_2 (left) and CO concentrations (right) in the middle of the kitchen, at a height of 2.4m.

5. Conclusions

A CFD tool has been used to simulate the thermal flow-field developing in a full-scale two-storey residential building during a fire. The considered building was constructed using a load-bearing steel frame combined with multi-layered gypsum plasterboard wall assemblies. Detailed physical properties have been used to describe the thermal behaviour of the various building materials; the effects of gypsum dehydration were taken into account by utilizing temperature-dependent properties for the gypsum plasterboards. Gas velocity and temperature predictions have been used to visualize the developing flow-field. Predicted wall temperatures allowed the assessment of the fire resistance behaviour of the investigated building. Finally, gas temperature and toxic gas concentration predictions allowed risk assessment for the tenants of the building. The ability of currently available CFD tools to effectively simulate fire spreading in realistic residential fire scenarios has been demonstrated. However, due to the complexity of the occurring physico-chemical phenomena, further validation studies are needed to assess the quantitative accuracy of the obtained predictions.

Acknowledgements

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